

HISTORICAL SURVEY OF THE QUASI-NUCLEAR BARYONIUM ^{*†}

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Abstract

We review ideas and speculations concerning possible bound states or resonances of the nucleon–antinucleon system.

1 Introduction

The question of possible nucleon–antinucleon ($N\bar{N}$) bound states was raised many years ago, in particular by Fermi and Yang[1], who remarked on the strong attraction at large and intermediate distances between N and \bar{N} .

In the sixties, explicit attempts were made to describe the spectrum of ordinary mesons (π , ρ , etc.) as $N\bar{N}$ states, an approximate realisation of the “bootstrap” ideas. It was noticed[2], however, that the $N\bar{N}$ picture hardly reproduces the observed patterns of the meson spectrum, in particular the property of “exchange degeneracy”: for most quantum numbers, the meson with isospin $I = 0$ is nearly degenerate with its $I = 1$ partner, one striking example being provided by ω and ρ vector mesons.

* Dedicated to the memory of C.B. Dover and I.S. Shapiro

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In the 70's, a new approach was pioneered by Shapiro[3], Dover[4] and others: in their view, $N\bar{N}$ states were no more associated with “ordinary” light mesons, but instead with new types of mesons with a mass near the $N\bar{N}$ threshold and specific decay properties.

This new approach was encouraged by evidence from many intriguing experimental investigations in the 70's, which also stimulated a very interesting activity in the quark model: exotic multiquark configurations were studied, followed by glueballs and hybrid states, more generally all “non- $q\bar{q}$ ” mesons which will be extensively discussed at this conference.

Closer to the idea of quasi-nuclear baryonium are the meson-meson molecules. Those were studied mostly by particle physicists, while $N\bar{N}$ states remained more the domain of interest of nuclear physicists, due to the link with nuclear forces.

2 The G-parity rule

In QED, it is well-known that the amplitude of μ^+e^+ scattering, for instance, is deduced from the μ^+e^- one by the rule of C conjugation: the contribution from one-photon exchange ($C = -1$) flips the sign, that of two photons ($C = +1$) is unchanged, etc. In short, if the amplitude is split into two parts according to the C content of the t -channel reaction $\mu^+\mu^- \rightarrow e^+e^-$, then

$$\mathcal{M}(\mu^+e^+) = \mathcal{M}_+ + \mathcal{M}_-, \quad \mathcal{M}(\mu^+e^-) = \mathcal{M}_+ - \mathcal{M}_-. \quad (1)$$

The same rule can be formulated for strong interactions and applied to relate $\bar{p}p$ to pp , as well as $\bar{n}p$ to np . However, as strong interactions are invariant under isospin rotations, it is more convenient to work with isospin eigenstates, and the rule becomes the following. If the NN amplitude of s -channel isospin I is split into t -channel exchanges of G -parity $G = +1$ and exchanges with $G = -1$, the former contributes exactly the same to the $N\bar{N}$ amplitude of same isospin I , while the latter changes sign.

This rule is often expressed in terms of one-pion exchange or ω -exchange having an opposite sign in $N\bar{N}$ with respect to NN , while ρ or ϵ exchange

contribute with the same sign. It should be underlined, however, that the rule is valid much beyond the one-boson-exchange approximation. For instance, a crossed diagram with two pions being exchanged contributes with the same sign to NN and $N\bar{N}$.

3 Properties of the NN potential

Already in the early 70's, a fairly decent understanding of long- and medium-range nuclear forces was achieved. First, the tail is dominated by the celebrated Yukawa term, one-pion exchange, which is necessary to reproduce the peripheral phase-shifts at low energy as well as the quadrupole deformation of the deuteron[5].

At intermediate distances, pion exchange, even when supplemented by its own iteration, does not provide enough attraction. It is necessary to introduce a spin-isospin blind attraction, otherwise, one hardly achieves binding of the known nuclei. This was called σ -exchange or ϵ -exchange, sometimes split into two fictitious narrow mesons to mimic the large width of this meson, which results in a variety of ranges. The true nature of this meson has been extensively discussed in the session chaired by Lucien Montanet at this Workshop. Refined models of nuclear forces describe this attraction as due to two-pion exchanges, including the possibility of strong $\pi\pi$ correlation, as well as excitation nucleon resonances in the intermediate states. The main conceptual difficulty is to avoid double counting when superposing s -channel type of resonances and t -channel type of exchanges, a problem known as “duality”.

To describe the medium-range nuclear forces accurately, one also needs some spin-dependent contributions. For instance, the P-wave phase-shifts with quantum numbers $^{2S+1}L_J = {}^3P_0$, 3P_1 and 3P_2 , dominated at very low energy by pion exchange, exhibit different patterns as energy increases. Their behaviour is typical of the spin-orbit forces mediated by vector mesons. This is why ρ -exchange and to a lesser extent, ω -exchange cannot be avoided.

Another role of ω -exchange is to moderate somewhat the attraction due to two-pion exchange. By no means, however, can it account for the whole repulsion which is observed at short-distances, and which is responsible of the saturation properties in heavy nuclei and nuclear matter. In the 70's, the short-range NN repulsion was treated empirically by cutting off or regularising the Yukawa-type terms due to meson-exchanges and adding some *ad-hoc* parametrization of the core, adjusted to reproduce the S-wave phase-shifts and the binding energy of the deuteron.

Needless to say, dramatic progress in the description of nuclear forces have been achieved in recent years. On the theory side, we understand, at least qualitatively, that the short-range repulsion is due to the quark content of each nucleon. This is similar to the repulsion between two Helium atoms: due to the Pauli principle, the electrons of the first atom tend to expel the electrons of the second atom. On the phenomenological side, accurate models such as the Argonne potential[6] are now used for sophisticated nuclear-structure calculations.

4 Properties of the $N\bar{N}$ potential

What occurs if one takes one of the NN potentials available in the 70's, such as the Paris potential[5] or one of the many variants of the one-boson-exchange models[7], and applies to it a G -parity transformation? The resulting $N\bar{N}$ potential exhibits the following properties:

1) ϵ (or equivalent) and ω exchanges, which partially cancel each other in the NN case, now add up coherently. This means that the $N\bar{N}$ potential is, on the average, deeper than the NN one. As the latter is attractive enough to bind the deuteron, a rich spectrum can be anticipated for $N\bar{N}$.

2) The channel dependence of NN forces is dominated by a strong spin-orbit potential, especially for $I = 1$, i.e., proton-proton. This is seen in the P-wave phase-shifts, as mentioned above, and also in nucleon-nucleus scattering or in detailed spectroscopic studies. The origin lies in coherent

contributions from vector exchanges (ρ , ω) and scalar exchanges (mainly ϵ) to the $I = 1$ spin-orbit potential. Once the G -parity rule has changed some of the signs, the spin-orbit potential becomes moderate, in both $I = 0$ and $I = 1$ cases, but one observes a very strong $I = 0$ tensor potential, due to coherent contributions of pseudoscalar and vector exchanges[8]. This property is independent of any particular tuning of the coupling constants and thus is shared by all models based on meson exchanges.

5 Uncertainties on the $N\bar{N}$ potential

Before discussing the bound states and resonances in the $N\bar{N}$ potential, it is worth recalling some limits of the approach.

1) There are cancellations in the NN potential. If a component of the potential is sensitive to a combination $g_1^2 - g_2^2$ of the couplings, then a model with g_1 and g_2 both large can be roughly equivalent to another where they are both small. But these models can substantially differ for the $N\bar{N}$ analogue, if it probes the combination $g_1^2 + g_2^2$.

2) In the same spirit, the G -parity content of the t -channel is not completely guaranteed, except for the pion tail. In particular, the effective ω exchange presumably incorporates many contributions besides some resonating three-pion exchange.

3) The concept of NN potential implicitly assumes the 6-quark wave function is factorised into two nucleon-clusters Ψ and a relative wave-function φ , say

$$\Psi(\vec{r}_1, \vec{r}_2, \vec{r}_3)\Psi(\vec{r}_4, \vec{r}_5, \vec{r}_6)\varphi(\vec{r}). \quad (2)$$

Perhaps the potential V governing $\varphi(\vec{r})$ mimics the delicate dynamics to be expressed in a multichannel framework. One might then be afraid that in the $N\bar{N}$ case, the distortion of the incoming bags Ψ could be more pronounced. In this case, the G -parity rule should be applied for each channel and for each transition potential separately, not at the level of the effective one-channel potential V .

4) It would be very desirable to probe our theoretical ideas on the long- and intermediate-distance $N\bar{N}$ potential by detailed scattering experiments, with refined spin measurements to filter out the short-range contributions. Unfortunately, only a fraction of the possible scattering experiments have been carried out at LEAR[9], and uncertainties remain. The available results are however compatible with meson-exchange models supplemented by annihilation. The same conclusion holds for the detailed spectroscopy of the antiproton-proton atom[10].

6 $N\bar{N}$ spectra

The first spectral calculations based on explicit $N\bar{N}$ potentials were rather crude. Annihilation was first omitted to get a starting point, and then its effects were discussed qualitatively. This means the real part of the potential was taken as given by the G -parity rule, and regularised at short distances, by an empirical cut-off. Once this procedure is accepted, the calculation is rather straightforward. One should simply care to properly handle the copious mixing of $L = J - 1$ and $L = J + 1$ components in natural parity states, due to tensor forces, especially for isospin $I = 0$ [8].

The resulting spectra have been discussed at length in Refs.[3, 11]. Of course, the number of bound states, and their binding energy increase when the cut-off leaves more attraction in the core, so no detailed quantitative prediction was possible. Nevertheless, a few qualitative properties remain when the cut-off varies: the spectrum is rich, in particular in the sector with isospin $I = 0$ and natural parity corresponding to the partial waves 3P_0 , $^3S_1 - ^3D_1$, $^3P_2 - ^3F_2$, corresponding to $J^{PC}I^G = 0^{++}0^+$, $1^{--}0^-$, $2^{++}0^+$, respectively. The abundant candidates for “baryonium” in the data available at this time[12] made this quasi-nuclear baryonium approach plausible[3, 13].

As already mentioned, annihilation was first neglected. Shapiro and his collaborators[3] insisted on the short-range character of annihilation and therefore claimed that it should not distort much the spectrum. Other au-

thors acknowledged that annihilation should be rather strong, to account for the observed cross-sections, but should affect mostly the S-wave states, whose binding rely on the short-range part of the potential, and not too much the $I = 0$, natural parity states, which experience long-range tensor forces.

This was perhaps a too optimistic view point. For instance, an explicit calculation[14] using a complex optical potential fitting the observed cross-section showed that no $N\bar{N}$ bound state or resonance survives annihilation. In Ref.[14], Myhrer and Thomas used a brute-force annihilation. It was then argued that maybe annihilation is weaker, or at least has more moderate effects on the spectrum, if one accounts for

1) its energy dependence: it might be weaker below threshold, since the phase-space for pairs of meson resonances is more restricted. It was even argued[15] that part of the observed annihilation (the most peripheral part) in scattering experiments comes from transitions from $N\bar{N}$ scattering states to a π meson plus a $N\bar{N}$ baryonium, which in turn decays. Of course, this mechanism does not apply to the lowest baryonium.

2) its channel dependence: annihilation is perhaps less strong in a few partial waves. This however should be checked by fitting scattering and annihilation data.

3) its intricate nature. Probably a crude optical model approach is sufficient to account for the strong suppression of the incoming antinucleon wave function in scattering experiments, but too crude for describing baryonium. Coupled-channel models have thus been developed (see, e.g., Ref.[16] and references therein). It turns out that in coupled-channel calculations, it is less difficult to accommodate simultaneously large annihilation cross sections and relatively narrow baryonia.

7 Multiquark states vs. $N\bar{N}$ states

At the time where several candidates for baryonium were proposed, the quasi-nuclear approach, inspired by the deuteron described as a NN bound state,

was seriously challenged by a direct quark picture.

Among the first contributions, there is the interesting remark by Jaffe [17] that $q^2\bar{q}^2$ S-wave are not that high in the spectrum, and might even challenge P-wave $q\bar{q}$ to describe scalar or tensor mesons. From the discussions at this Workshop in other sessions, it is clear that the debate is still open.

It was then pointed out[18] that orbital excitations of these states, of the type $(q^2) - (\bar{q}^2)$ have preferential coupling to $N\bar{N}$. Indeed, simple rearrangement into two $q\bar{q}$ is suppressed by the orbital barrier, while the string can break into an additional $q\bar{q}$ pair, leading to q^3 and \bar{q}^3 .

Chan and collaborators[19, 20] went a little further and speculated about possible internal excitations of the colour degree of freedom. When the diquark is in a colour $\bar{3}$ state, they obtained a so-called “true” baryonium, basically similar to the orbital resonances of Jaffe. However, if the diquark carries a colour 6 state (and the antidiquark a colour $\bar{6}$), then the “mock-baryonium”, which still hardly decays into mesons, is also reluctant to decay into N and \bar{N} , and thus is likely to be very narrow (a few MeV, perhaps).

This “colour chemistry” was rather fascinating. A problem, however, is that the clustering into diquarks is postulated instead of being established by a dynamical calculation. (An analogous situation existed for orbital excitations of baryons: the equality of Regge slopes for meson and baryon trajectories is natural once one accepts that excited baryons consist of a quark and a diquark, the latter behaving as a colour $\bar{3}$ antiquark. The dynamical clustering of two of the three quarks in excited baryons was shown only in 1985[21].)

There has been a lot of activity on exotic hadrons meanwhile, though the fashion focused more on glueballs and hybrids. The pioneering bag model estimate of Jaffe and the cluster model of Chan et al. has been revisited within several frameworks and extended to new configurations such as “dibaryons” (six quarks), or pentaquarks (one antiquark, five quarks). The flavour degree of freedom plays a crucial role in building configurations with maximal attraction and possibly more binding than in the competing threshold. For

instance, Jaffe pointed out that (uuddss) might be more stable than two separated (uds) [22], more likely than in the strangeness $S = -1$ or $S = 0$ sectors. In the four-quark sector, configurations like $(QQ\bar{q}\bar{q})$ with a large mass ratio $m(Q)/m(\bar{q})$ are expected to resist spontaneous dissociation into two separated $(Q\bar{q})$ mesons (see, e.g., [23] and references therein). For the Pentaquark, the favoured configurations $(Q\bar{q}^5)$ consist of a very heavy quark associated with light or strange antiquarks [24, 25].

In the limit of strong binding, a multiquark system can be viewed as a single bag where quarks and antiquarks interact directly by exchanging gluons. For a multiquark close to its dissociation threshold, we have more often two hadrons experiencing their long-range interaction. Such a state is called an “hadronic molecule”. There has been many discussions on such molecules [26, 27, 28, 29, 30, 31, 32, 33, 34], $K\bar{K}$, $D\bar{D}$ or BB^* . In particular, pion-exchange, due to its long range, plays a crucial role in achieving the binding of some configurations. From this respect, it is clear that the baryonium idea has been very inspiring.

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